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MAGNETIC SHIELDING FOR THE LONG-PULSE, PURE-BEAM SOURCE NEUTRALIZERS ON THE MFTF-B

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Abstract

Present ion sources produce deuterium ions plus small amounts of impurity ions including oxygen. The oxygen current is readily trapped by the Mirror Fusion Test Facility-B (MFTF-B) plasma and represents a severe energy loss mechanism. A pure-beam source-neutralizer has been designed by LLNL for the MFTF-B. This concept uses momentum separation by closely coupling an electromagnet to the source to purify the beam.[5] This design requires a low pressure in the neutralizer, implying a long length and a large diameter for high conductance. Present designs require a 55-in. diameter by 60-in. long magnetically shielded region. This shield encloses the source and the separator magnet, and acts as the neutralizer duct for the beam. The fringe fields from the MFTF-B magnets penetrate the pure-beam neutralizer along the beamline axis. Field strengths on the order of three hundred gauss must be reduced to less than 6 gauss axial and 0.2 gauss transverse to the beam. Conventional single and double layer shielding designs require excessive amounts of permeable material. Multiple layer shields using a soft iron outer shield with a highly permeable inner shield require a 4 3/4-in.-thick outer shield. We have rejected this as a possible shielding solution. Active shielding, using two bucking coils around a 2-in.-thick iron tank, has been designed. This design has been tested using scale models. These tests measured the flux into cylinders of various thicknesses, and the magnetic field on axis of this shield was recorded. Tests were made in both a uniform and nonuniform fields. This information has been used to locate the bucking coils outside the magnetic shields. Measurements made with this shield design show that we can effectively meet the magnetic shielding requirements for the long-pulse, pure-beam source neutralizer on the MFTF-B.

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Introduction

The Mirror Fusion Test Facility-B (MFTF-B) experiment was designed for 30 second operation. Plasma confinement in this experiment requires neutral beams to fuel the central cell, to help build the axial confining potential, and to charge-exchange pump the anchor regions. The neutral beams, which consist of an ion-source, accelerator, and neutralizing section must operate for long (30-s) pulses in magnetic fringe fields of several hundred gauss. Magnetic shielding is required in these high fields not only to ensure proper ion-source operation but also to maintain small divergences[1] of the extracted beam.

The 30-s neutral beams on the MFTF-B will be located at the axicell, transition, and anchor regions of the magnetic field (Fig. 1). The plasma energy and density of the thermal barrier, which is presently located in the transition region, are very sensitive to plasma impurities, most of which are injected with the beam of hydrogen particles. Ott et al.[2] have shown that 0.5% or more of a hydrogen beam is composed of oxygen, which is the highest impurity of concentration in the plasma.

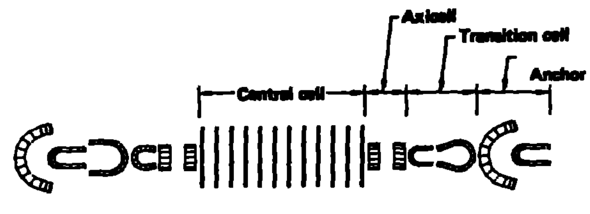

Fig. 1 MFTF-B Magnet Coil Set

Thermal barrier operation of the MFTF-B requires that the oxygen content of the 30 second neutral beams be less than one part in 10^6. The proposed method for achieving this low level uses a momentum separation technique in which a closely-coupled magnetic field separates the ion species downstream of the accelerator.[3,4] The full energy species, i.e., the pure beam, is aimed at the plasma target. This concept has been successfully tested using a Lawrence Berkeley Laboratory (LBL) long-pulse source.[5]

The pure-beam design, shown in Fig. 2, has a 55-in. (139.7 m) diameter and 163-in. (415 m) length, because of vacuum pumping and ion-beam neutralization considerations. The field in the neutralizer must be below an average value of 2.5 G for negligible beam divergence[1] and less than 0.2 G transverse to the beam for aiming considerations. The aiming limit was determined by the technique given in ref. 6.

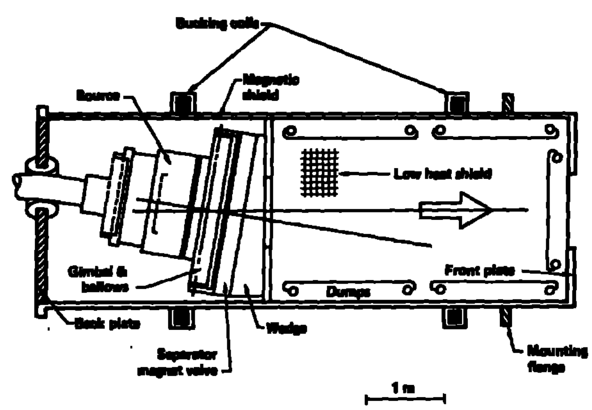

Fig. 2 Pure-Beam Final Design for the MFTF-B

The ion source must also be shielded. Source shielding requirements were determined by LBL from a series of experiments. The experimental results show that effective source operation occurs when the fringe fields are less than 6 G on axis, .3 G transverse to the wide side of the beam, and 2 G transverse to the narrow side of the beam. These limits are higher than the neutralizer limits and can be achieved by proper neutralizer shielding.

The pure-beam magnetic shield has evolved from calculations and scale model tests to the present design shown in Fig. 2. The design process began with the considerations. The final design and the scale model tests that were done to verify this configuration are presented in the third section of this paper.

Preliminary Design Considerations

The initial pure-beam shielding design consisted of separate shields for the neutralizer and the source, called the source/neutralizer shield, as shown in Fig. 3. This was designed to have a shielding factor of 1500, where S is defined by

$$S = \frac{Hext}{Hi} , \qquad (1.1)$$

and Hext is the external field and Hi the internal field inside the shield. The neutralizer shield design was a simple cylinder with end caps that had apertures for beam transmission. The source shield was a separate 2-in.-thick cylinder mounted to the neutralizer.

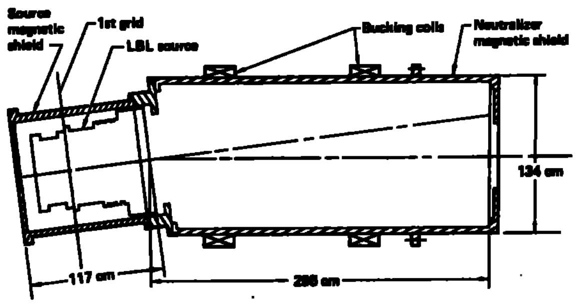

Fig. 3 Initial Pure-Beam Magnetic Shield Design Consisting of Separate Source and Neutralizer Shields.

A one-tenth scale model of the source-neutralizer shield was designed using C1010 steel with neutralizer thicknesses of 0.1, 0.2, and 0.4 in. and tested in uniform magnetic fields of 135, 264, and 398 gauss. Typical results from these tests are shown in Fig. 4,

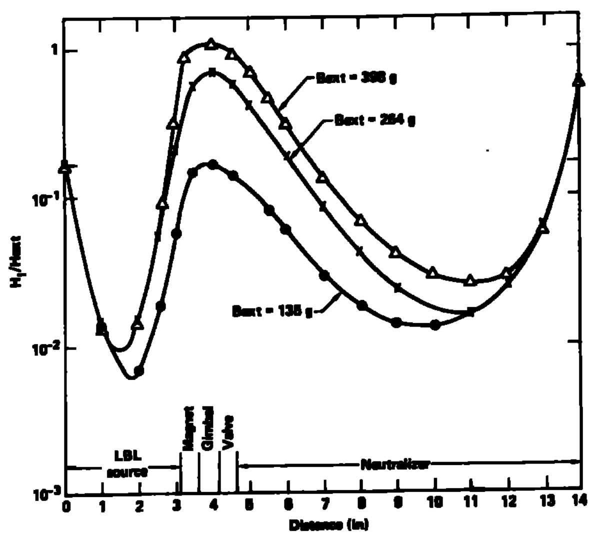

Fig. 4 Plot of S^{-1} Versus Distance Inside the Shield of Fig. 3 Where the External Field is Directed Along the Axis of the Neutralizer.

in which S^{-1} is plotted vs distance along the axis of the neutralizer. Data were taken at 1-in. intervals from the front plate of the neutralizer through the source shield. The results of this test show that the soft iron saturates where the source shield attaches to the neutralizer shield.

Various improvements to the source-neutralizer shield were tried, with results similar to those shown in Fig. 4. A detailed analysis showed two problems affecting the performance of this design. The first problem relates to the geometry change that occurs between the source and the neutralizer. This was verified by performing a two-dimensional calculation using the POISSON code 7 to determine the shielding effectiveness. The computational model used two cylinders that were proportional to the test-model dimensions but with the cylinders joined along one common axis. The end caps were also modeled, and the results of this calculation are shown in Fig. 5. This analysis showed an order of magnitude decrease in S where the source is connected to the neutralizer.

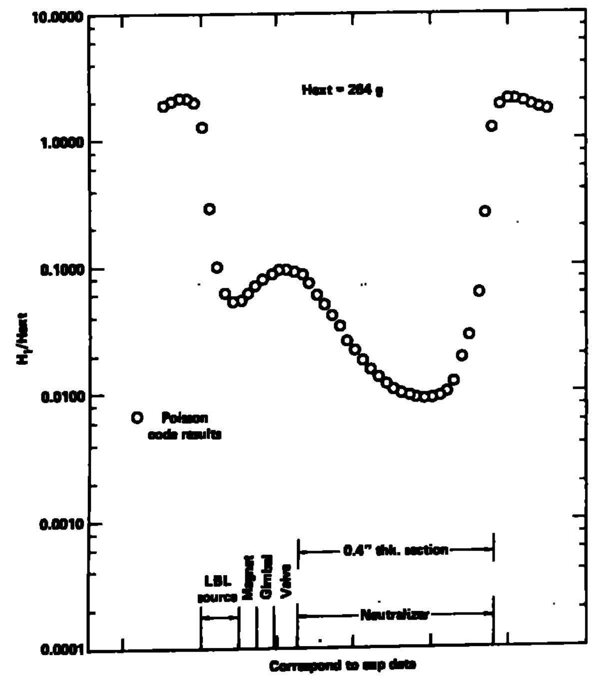

Fig. 5 Results of Two-Dimensional Model of the Shield Shown in Fig. 3 Using the POISSON Code.

The second source of field leakage in this design occurs because of the mechanical connection of the source shield where it is mounted onto the neutralizer shield. This mechanical connection introduces a physical gap that degrades the shield performance.[8] Even when the model shield mating surfaces were machined flat and parallel to one another using number 32 surface-finish tolerances, the gaps still presented significant problems. This problem is compounded by the fact that the shielded parts must be annealed after machining to obtain the best magnetic properties, but this annealing can warp the mating surfaces, increasing the gap spacing. We have estimated that the gap between the source and neutralizer shields will decrease S by a factor of 2 to 4.

Because the gap and geometry change between the source and the neutralizer effectively cause this shield to saturate, it was necessary to consider a different design. The new design also accounts for the source potential of 80 kV that must be isolated from the grounded magnetic shield. Source voltage breakdown is avoided by combining a relatively large radius of curvature on source electrical shields with a nominal 7-in. clearance between the electrical shield and the ground plane. The magnetic shield had to enclose both the source and the neutralizer with a continuous shield and maintain the proper internal dimensions to prevent source voltage breakdown. This shield design is the cylinder shown in Fig. 2.

The cylindrical magnetic shield represents a solution to the pure-beam shielding problem on the MFTF-B, but it is not a trivial solution. The pure-beam locations on the MFTF-B are in fringe fields that are axial to the beam and are as low as 110 G at the neutralizer front plate for the HEPB beam and as high as 300 G for the axicell and anchor beams. The shielding techniques that were applied in developing the cylindrical shield were passive shielding, which uses only permeable material, and active shielding, which combines permeable material with bucking fields generated by current loops.

A passive shield uses soft magnetic material to create the field-free region. The simplest passive design considered was a single shield made of high-permeability Allegheny Ludlum 4750 (AL4750), a nickel-iron compound. The high permeability is needed to obtain the low internal fields of 0.2 G. Single-shield calculations[*] based on a uniform 300 G fringe field show that this design has a shield thickness greater than 9-in. and weight of approximately 45 t. The thick material is needed because of the low saturation capacity of the alloy.

A multiple passive shield in a uniform 300 g field was next considered, with the outer shield is made of C1010 steel and inner liners of AL4750. The outer shield was analyzed as a single and multiple steel layer design. The results of this analysis showed that the outer steel layer had to be 4.75-in.thick for the single layer design. The multiple steel shield produced steel thicknesses larger than the single layer design even though optimum gap spacing between layers was used. This calculation shows that the multiple-layer design is useful when each shielding layer reduces Hi in the gap between layers to values below the knee of the B-H curve. This technique is therefore most effective when multiple shielding materials are used. The multiple-layer shield for the pure-beam neutralizers was still too thick (4.75-in.) and massive (24 t) to be considered a practical solution.

The next magnetic shield designed used solenoid coils, placed around the cylinder, to buck out the fringe field. This technique was tried on a scale-model cylindrical shield using a single coil at the cylinder midplane. In this experiment the magnetic flux into the shield was measured with a Keithley 614 electrometer and a pickup coil around the shield. The current generated in the pickup coil is proportional to the flux change in the shield. The flux changes either by moving the pickup coil to a new location along the shield or by turning the external field on and off. A base flux measurement over half of the shield was made without the bucking coils for various cylinder thicknesses and at several external field values. Typical results of this measurement are shown in Fig. 6. Measurements were taken over only half the shield, since the flux is symmetric about the shield midplane. Once the total flux without the bucking coil was measured, a single bucking coil was placed at the shield midplane, and the current in this coil was increased until Hi at the shield midplane became zero. The flux was again measured over half the cylinder length and, as shown in Fig. 6, it was significantly reduced from the no-bucking-coil case. The bucking coils used in this test were approximately 1.5 in. wide.

It was thought that by placing two coils side by side at the midplane, producing a 3-in.-wide solenoid coil, a significantly better shield could be made. Fig. 6 shows that the wider coil improved the shield slightly. Although the wide coil did not solve the total shielding problem, this test did prove that active shielding could be accomplished using shield thicknesses as small as 1 in. The major design problem that remained was to determine the number of coils and the shield thickness.

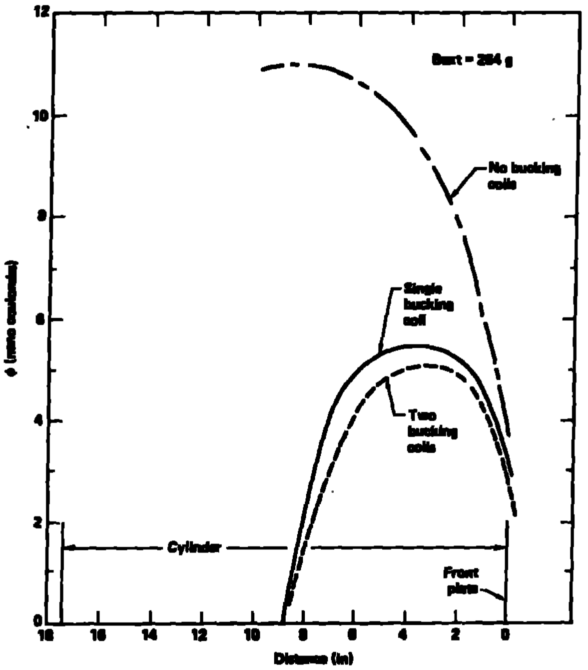

Fig. 6 Flux Measurements on the one-tenth Scale Model Cylindrical Pure-Beam Magnetic Shield With 0.25-In.-Thick Walls and an Axial External Field of 264 G.

Magnetic Shielding Design Of The Pure-Beam Neutralizers

Once active shielding was established as a viable design for the pure-beam neutralizer, it was necessary to determine the shield thickness, number of bucking coils, and coil placement around the neutralizer. The first step was to determine the number of bucking coils required for the shield. This was done experimentally by using a one-tenth scale model of the pure-beam neutralizer with 0.25-inch-thick walls and two solenoid coils. In one experiment, the coils were placed at a distance L/3 from the end of the neutralizer, where L is the total shield length. In the second experiment, a three-coil system was simulated by placing one coil at the shield midplane and another at L/4 from the end. The third coil was not necessary because of symmetry considerations. The results of these experiments are shown in Fig. 7. This shows that two bucking coils are adequate to produce acceptable shielding.

The next step was to determine an optimum shield thickness. Three scale-model shields with thicknesses of 0.125, 0.25, and 0.375-in. were tested using two bucking coils. The result was inconclusive since all three models operated satisfactorily when the bucking fields were properly adjusted. The general trend in the data showed that the thicker shields required less bucking field and therefore less power. Although thick shields are more desireable from a power standpoint, the weight, cost, and manufacturing problems of thick shields are undersirable. Similarly, thin shields require high bucking fields

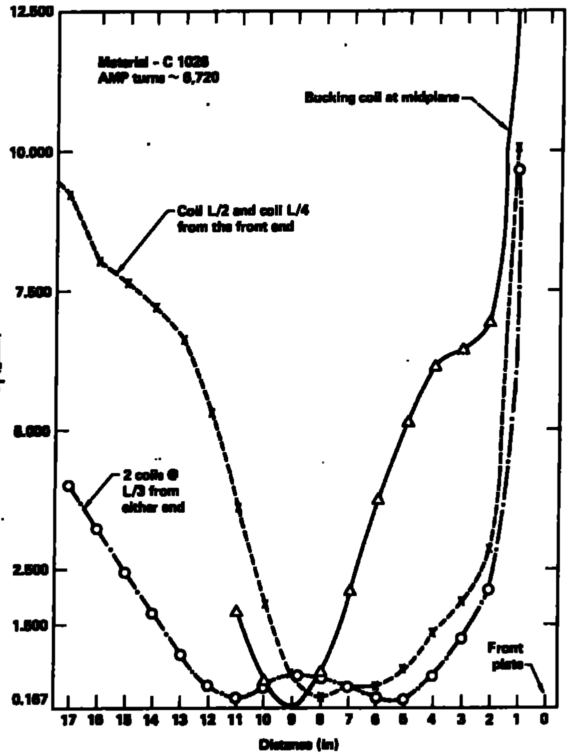

Fig. 7 Internal Magnetic Fields in the one-tenth Scale Model Cylindrical Shield for Bucking Coil at the Midplane, (X) Coils at 1/2 and L/4 Along the Shield, and (O) at L/3 Along the Shield.

which require coils with a large number of ampere turns. In the design for the pure-beam shield, the thickness was chosen as 2 in. because this is the largest thickness that can be easily manufactured into a cylindrical tank. Tradeoff studies comparing shield thickness savings with magnet and power supply costs must be made to choose an optimum combination of material thickness and coil configuration.

Once the number of bucking coils was determined, their location along the shield had to be found. In another series of experiments, the magnetic shield with two bucking coils was placed in magnetic fields that approximated the gradients of the MFTF-B. The field level at the front of the neutralizer was set at 264 G for one test and 398 G for the second.

Field levels inside the shield along the axis were measured using a three-axis Hall probe attached to a Bell gaussmeter. The bucking coils were positioned at several axial positions along the shield and internal field data were taken for each location. This experiment showed that the optimum coil location for the gradients tested occurred when the coils were at 0.40L and 0.86L. The data for this experiment are shown in Fig. 8.

The bucking coils were moved ± 1 in. from the optimum position, and it was shown that the active shield still maintained the internal magnetic field levels to values below the required minimums. Field values approximately 1/2 in. off the shield axis were also measured to test the shielding near the edge of the neutral beam. These experiments also showed that active shielding with two bucking coils can adequately shield the pure-beam neutralizer.

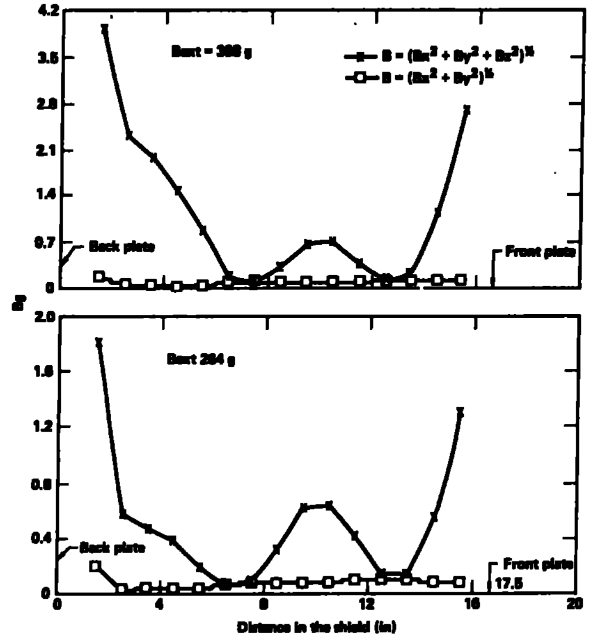

Fig. 8 Internal Field of the one-tenth Scale Model Cylindrical Shield in a Gradient Field Similar to the Gradient Fields of the MFTF-B.

Conclusion

It has been demonstrated by a series of one-tenth scale model tests that the long-pulse, 30-s pure-beam neutralizers developed at LLNL can be magnetically shielded using an active shielding technique. The active shield is composed of two bucking coils placed along the axis of the 55-in.-diameter by 163-in.-long and 2-in.-thick C1010 shield. This arrangement has been shown in scale model tests to produce internal fields along the neutralizer less than 0.2 G transverse to the neutral beam and less than 2 G along the axis of the beam. The bucking coil placement depends on the external field gradient, but adequate shielding occurs over large axial distances, approximately 10 in. in the full-scale design, indicating that the optimum occurs over a fairly flat region.

The shield design presented in this paper represents a generic design which is applicable to the proposed 30-s beamlines on the MFTF-B. A final design of this shield which considers cost optimization between the shield thickness, coil, and power supply costs remains to be done.

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